The reality of relations: the case from quantum physics

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Abstract

As far as classical physics is concerned, it is possible to trace causal relations between physical objects (i.e. particles in this case) back to intrinsic properties of these objects (such as their mass and charge). On this view, causal relations turn out to be internal instead of external relations, supervening on intrinsic properties of the relata (as proposed by Heil and Lowe). However, one can raise doubts about this view already in Newtonian mechanics. The decisive blow to this view comes from quantum physics, with Bell's theorem proving that no dynamics based on local, intrinsic properties of quantum objects can yield the empirical predictions of quantum mechanics. Nonetheless, quantum entanglement by no means implies that we have to abandon an ontology of objects (i.e. substances such as particles) in favour of an ontology of structures (as claimed by French and Ladyman). Any of the known proposals for a quantum ontology of matter in space-time is committed to objects. However, on any of these proposals, what determines the dynamics of these objects are not local, intrinsic properties, but a global or holistic property instantiated by all the objects together – that is, a structure that takes all the objects in the universe as its relata. The view set out in this paper thus amounts to combining ontic structural realism with an ontology of objects that can be conceived as substances. This suggestion is illustrated by drawing on the ontology of quantum physics worked out by Bohm and Bell.

1. Introduction

On the one hand, E. J. Lowe (this volume) and John Heil (this volume, and see Heil 2012, ch. 7) argue for an ontology according to which there are no fundamental relations. There are objects (substances), these objects have intrinsic properties, and all the relations among these objects are internal relations in that they supervene on their intrinsic properties. Internal relations thus are no addition to what there is. On the other hand, James Ladyman (this volume, and see Ladyman and Ross 2007, chs. 1-4) argues for an ontology according to which relations in the sense of structures are fundamental. This difference in content goes together with a difference in methodology: Lowe and Heil pursue a traditional metaphysics based on *a priori* reflection. Although this metaphysics is supposed to match natural science, the metaphysics is not developed by means of considering our best physical theories. Ladyman, by contrast, seeks to naturalize metaphysics: metaphysical claims are justifiable only insofar as they can be extracted from our best fundamental physical theories and provide for an ontology of these theories.

This paper takes a middle ground, both as regards the content as well as regards the method of metaphysics. As far as the methodology is concerned, it seeks to make a case for a natural philosophy that treats physics and metaphysics as one whole, being inseparable, without it being possible to accord priority to the one over the other. Thus, metaphysical claims can neither be directly read off from the formalism of physical theories, nor can they be based on *a priori* reasoning. As far as the ontology is concerned, the paper argues that the challenge to a metaphysics that relies on a commitment to substances and intrinsic properties stems from the relations of quantum entanglement, with Bell's theorem ruling out the possibility of reducing these relations to something that is not a fundamental, dynamical relation. However, these relations are instantiated by objects (substances) that are individuated independently of these relations. In other words, as far as contemporary fundamental physics is concerned, there is no cogent reason to abandon the Aristotelian ontology of substances and properties, but quantum physics shows that the properties are holistic properties of the configuration of matter as a whole and hence relations, instead of intrinsic properties of individual substances.

In the following, I shall argue for this methodology as well as for this ontology by considering in the first place Newtonian mechanics, pointing out how this theory can be taken to fit the view of Lowe and Heil (section 2), and then show what exactly changes in the transition to quantum physics and how that change puts a constraint on the future development of fundamental physics (section 3).

2. *The ontology of Newtonian mechanics*

At the end of the "Opticks" (1704), Newton writes:

> … it seems probable to me, that God in the Beginning form'd Matter in solid, massy, hard, impenetrable, moveable Particles … the Changes of corporeal Things are to be placed only in the various Separations and new Associations and Motions of these permanent Particles. (Question 31, p. 400 in the edition Newton 1952)

Newton's natural philosophy (*philosophia naturalis*) can be seen as replying to three questions. The first question is this one: *What are the physical objects?* Newton's answer is that matter consists in particles that are distributed in a background space, a particle being a material object that is so small that it is localized at a point in space, thus being indivisible. Hence, some points of space are occupied – a particle is localized at them –, whereas other points are empty.

If one adopts a sparse view of physical properties, there is no reason to make use of the notion of properties as far as this basic characterization of matter is concerned. Matter is primitive stuff, and it is a primitive fact that some points of space are occupied whereas others are not. There is a good reason for conceiving matter in terms of particles, that is, in terms of points of space being occupied or empty. If one considered matter to be a continuous stuff distributed all over space (that is, gunk), then one would have to maintain that there is more stuff at some *points* of space and less stuff at others in order to be able to accommodate variation. But it could not be a primitive matter of fact that there is more stuff at some points of space and less at others; a property of the stuff would be needed to account for that difference. However, as I shall argue shortly, all the properties that classical mechanics attributes to matter concern its temporal development, not simply the fact that there is matter. The view of matter consisting in particles can easily pay heed to the fact that there is more matter in some *regions* of space than in others: in some regions of space, more points are occupied than in others.

The distribution of matter in a background space develops in a background time. That is to say, as time passes, there is change in which points of space are occupied and which are empty. That change is such that the particles persist in the sense of enduring, each moving on a continuous trajectory. Consequently, each particle has an identity in time by which it distinguishes itself from all the other particles. The particles can therefore with good reason be regarded as substances. The fact that there is change implies that Newton has to answer a second question: *What are the laws of the temporal development of the physical objects?* More precisely: *What are the properties of the physical objects so that certain laws describe their behaviour?* Thus, the need for a commitment to properties arises in Newton's natural philosophy when it comes to an account of the temporal development of the physical objects.

The fact that there is change means that the particles have the property of velocity, velocity being the first temporal derivative of position. That is to say, over and above having an initial position, the particles have an initial velocity, which makes them move in a certain manner. The property of velocity of each particle is conserved, as long as it is the only property that is taken into consideration. Thus, velocity gives rises to Newton's first law, which says that given an initial velocity, particles move on a straight line with constant velocity (inertial motion). However, it is an empirical fact that there is not only change in the points in space that particles occupy as time passes, but also change in their state of motion, that is, change in velocity. That is why it is necessary to attribute more properties to the particles than just an initial velocity.

Newton does so in taking the particles to be equipped with mass. In virtue of possessing mass, particles accelerate in the sense that they attract each other (gravitational mass) as well as resist to acceleration (inertial mass), acceleration being the change of velocity in time and thus the second temporal derivative of position. Newton's second law describes how properties change the state of motion of particles. It does so by relying on the notion of forces. Thus, in virtue of possessing mass, particles exert a force of attraction upon each other, namely the force of gravitation. However, there is no need to subscribe to an ontological commitment to forces over and above a commitment to properties of the particles such as their mass. Given the masses of the particles, the force of gravitation ensues. It is no addition to being.[1] The same goes for other properties that account for the change of the state of motion of particles in classical physics, such as their charge, giving rise to the electromagnetic force.

Finally, Newton's natural philosophy has to answer a third question: *How do the physical objects and their properties explain the observable phenomena?* As the quotation above shows, Newton answers this question by maintaining that (a) all macrophysical objects are composed of microphysical particles and that (b) all differences in macrophysical objects can be traced back to the position (arrangement) and the change of position (motion) of the microphysical particles. That is to say, the properties that account for the temporal development of the position of the particles (that is, their initial velocity and their mass, as well as their charge) thereby also account for all the variations in the macrophysical objects.

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1 As regards the discussion about the ontological status of Newtonian forces, see notably Bigelow, Ellis and Pargetter (1988), Wilson (2007) and Massin (2009).

Newton's theory is a paradigmatic example of natural philosophy in that physics and metaphysics come together in this theory in an inseparable manner. Newton's theory is not a naturalized metaphysics in the sense of being a positivist metaphysics: the assumption that there are particles and that properties of the particles have to be admitted that change the state of motion of the particles by accelerating them cannot be derived from any observation. It is an ontological postulate. But Newton's theory is not an *a priori* metaphysics either: there is no *a priori* justification of the commitment to particles and properties that accelerate them. Making these assumptions yields a theory that is both physical-mathematical and metaphysical, being a universal physical theory that has the ambition to provide for a complete ontology of nature, and whose justification consists in its success in predicting and explaining the observable phenomena.

Let us now consider in more detail the properties that determine the state of motion of the particles such as their mass. Is mass an intrinsic property of the particles? A world in which only one point of space is occupied at any time – that is, a world with only one particle – is a possible world of Newtonian mechanics, given that Newton admits a background space and a background time. That one particle would forever continue to be in inertial motion (or to be at rest). Consider the widespread view according to which an intrinsic property is a property that an object possesses independently of being alone in a world or being accompanied by other objects.[2] On this view, mass counts as an intrinsic property (as does velocity).

However, a world in which there is only one particle with mass would be indiscernible from a world in which there is only one massless particle. In other words, taking the particle to be equipped with the property of mass over and above the fact of a point of space being occupied makes no difference as long as one limits oneself to considering possible worlds in which only one point of space is occupied at a time. But the lack of a difference in the case of a one particle world does not decide against mass being an intrinsic property of the particles.

If matter is primitive stuff, properties are needed only to account for the manner in which the distribution of the primitive stuff in space varies in time, that is, to account for the way in which the matter moves. Properties that are admitted in order to do that job are dispositions in the sense of properties for which it is essential to play a certain role as described by a law. Hence, the answer to the question of whether mass is an intrinsic property in Newtonian mechanics depends on whether or not dispositions are intrinsic properties.

One can with good reason take dispositions to be intrinsic properties. The fact that it is essential for them to perform a certain role as described by a law – make matter accelerate in a certain manner in the case of mass – does not turn them into relations. Any theory of dispositions has to acknowledge the possibility of situations (possible worlds) in which the disposition in question exists, but is not manifest. That is to say, any theory of dispositions has to allow for situations (possible worlds) in which the disposition in question exists, but which are indiscernible from a situation (possible world) in which the disposition in question does not exist – as in the case of a Newtonian world with one particle that has mass and a Newtonian world with one particle that does not have mass.

Hence, as far as Newtonian mechanics is concerned, one can indeed make a case for the position advanced by Lowe and Heil, namely that causal relations can be traced back to

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2 See Langton and Lewis (1998 and 2001), as well as Hoffmann-Kolss (2010, first part) for a detailed discussion.

properties of substances (i.e. particles) that are dispositions and intrinsic properties. Causal relations are the manifestations of these dispositions, their effect being change in the distribution of matter in space. These are internal relations in the sense that they supervene on dispositions that are intrinsic properties of the relata. Consequently, apart from Newton's admission of a background space and a background time, there is no need to be committed to anything more than substances (particles) and intrinsic properties of these substances that are dispositions, manifesting themselves in a certain form of motion of the particles.

Instead of regarding mass as a disposition, one may maintain that it is an intrinsic property, but that it exercises the role of changing the state of motion of the particles as described by the law of gravitation only contingently. That is to say, in other possible worlds, mass plays another role. More precisely, considering two different properties (say, mass and charge), it is possible that they swap their roles: in a world w_2, mass plays the role that charge plays in the actual world w_1, and charge plays in w_2 the role that mass exercises in the actual world w_1. This view implies that the essence of a property – what the property is – is separated from the role that it exercises in a world as described by a law. But what then is the essence of a property? The answer to this question that is dominant in the literature holds that it is a pure quality, known as quiddity (Lewis 2009); but one may also suggest that properties have a primitive numerical identity (Locke 2012).

However, neither of these answers seems convincing: one may contemplate admitting a primitive numerical identity when it comes to primitive stuff filling space, for that stuff is nothing else but what occupies space, as are Newtonian particles as sketched out above. But if one attributes properties to that stuff, it seems odd to admit a primitive numerical identity for these properties as well, for there would then be no reason to take the primitive stuff that occupies space to be equipped with properties at all; one has a reason to recognize properties of the stuff if and only if one wants something that performs a certain job for the temporal development of the stuff. As far as the view of properties being pure qualities is concerned, the problem is that it is not intelligible what could constitute a purely qualitative difference between two properties (say, mass and charge), given that all the accessible difference that justifies recognizing two different properties consists in a difference in the function that these properties exercise for the temporal development of the distribution of matter in space as expressed by a law.

The same objection applies to the mixed view of properties of Martin (1997) and Heil (2003, ch. 11, and 2012, ch. 4) according to which properties are both qualitative and dispositional in one. Again, the question is what could constitute a difference in the qualitative aspect of properties such as mass or charge, or what could constitute a reason for admitting a qualitative difference that accompanies the difference in the role that properties such as mass and charge exercise. Again, one needs properties in one's ontology of the natural world only if one wants something that performs a certain function for the behaviour (that is, the temporal development) of the objects that have the properties in question. But then it is sufficient to admit properties that are dispositions *tout court*, that is, properties whose essence it is to exercise a certain role as described by a law (see notably Bird 2007). There is no risk of a regress or a paradox here, since these properties are instantiated by substances whose behaviour they determine.

Whereas one can thus make a firm case for physical properties being dispositions, one may nevertheless raise a doubt about mass being an intrinsic property in Newtonian mechanics.

The reason is that, although the strength of the force of gravitational attraction between two objects in virtue of each of them possessing a mass depends on their spatial distance, the force is supposed to be transmitted instantaneously through empty space without a medium. That is why Newton's theory is taken to be committed to action at a distance: the presence of a mass in space at a given time t changes the state of motion of all the objects elsewhere in space at that very t.

However, one may question whether the notion of an *instantaneous* action at a distance makes sense: when there is an object with a certain mass somewhere in space at a given time t, the manifestation of its mass is present strictly speaking in all the other objects in the universe *at that very instant t*. Consequently, there is no room for an interaction in the sense of the transmission of something. Consider what van Fraassen points out in another context (the context is the discussion of non-local quantum correlations to which I will turn in the next section):

> To speak of instantaneous travel from X to Y is a mixed or incoherent metaphor, for the entity in question is implied to be simultaneously at X and at Y – in which case there is no need for travel, for it is at its destination already. … one should say instead that the entity has two (or more) coexisting parts, that it is spatially extended. (van Fraassen 1991, p. 351)

These considerations suggest taking mass to be a relation among the objects in space rather than an intrinsic property of each object. That is to say, there is one instantiation of a holistic property of mass distribution at any t that relates all the objects in the universe and that fixes how each of them changes its state of motion at t. This relational view of mass can admit a possible world with only one particle as limiting case: there is exactly one instantiation of mass distribution at any t also in that universe, but since there is only one particle that instantiates the mass distribution, there is no change in its state of motion. Thus, already in the context of Newtonian mechanics, one can argue for the view of there being one holistic dispositional property of mass distribution relating all the substances in the universe, instead of each of them possessing an intrinsic property that determines the state of motion of the substances.

3. *The ontology of quantum mechanics*

Any discussion of the issue of what quantum mechanics tells us about the world faces the problem that on the one hand we have a precise formalism for the calculation of probabilities for measurement outcomes at our disposal, but that on the other hand this formalism does not wear an ontology on its sleeves – it is not possible to read any ontological consequences directly off from the formalism. The following, easily accessible thought experiment suggested by Einstein at the Solvay conference in Brussels in 1927 illustrates this situation (my presentation is based on Norsen 2005): consider a box prepared in Brussels with exactly one particle inside the box. The box is split in two halves in Brussels, one half is sent to New York, the other half is sent to Tokyo. Suppose that Alice in New York opens the box she receives and finds it to be empty. If Alice's box is empty, it then is a fact that there is a particle in the box that Bob receives in Tokyo.

The quantum formalism represents the particle in the box by means of a wave-function. When the box is split and the two halves are sent to New York and to Tokyo, the wave-function represents the particle in terms of a superposition of its being in the box that travels to New York and its being in the box that travels to Tokyo. The operational meaning of this representation is that there is a 50% chance of finding the particle in the box that travels to New York and a 50% chance of finding the particle in the box that travels to Tokyo. When Alice in New York opens the box she receives and finds it to be empty, the representation by means of the wave-function changes such that the wave-function represents the particle to be located in the box that travels to Tokyo. That sudden change is known as collapse of the wave-function.

One may try an ontological reading of the wave-function in the sense that it provides a literal and thus complete representation of what happens with the particle in this situation. But one then faces the consequence that the collapse of the wave-function means that Alice's action of opening the box she receives in New York instantaneously brings it about that there is a particle localized in the box in Tokyo. That is what Einstein considered to be spooky action at a distance. One may therefore turn to an epistemological reading of the wave-function in the sense that it provides all the information about the temporal development of the particle that we can obtain, without being able to represent the actual trajectory that the particle takes. On this reading, the collapse of the wave-function upon Alice's opening of the box she receives in New York simply represents a change in the state of knowledge of the observer – once one box has been opened, we know where the particle is, whereas before opening the box, we were ignorant of where it is. This reading implies that the particle always travels on a classical trajectory, being in one box and not being influenced by whatever operation is performed on the other box. This is Einstein's reading of this thought experiment – according to him the only reading that avoids having to acknowledge spooky action at a distance.

However, that reading was refuted by Bell's theorem in 1964 (reprinted in Bell 2004, ch. 2) for the general case, that is, when one considers at least two particles and two different observables. In order to understand that refutation, we have to turn to the thought experiment that Einstein published together with Podolsky and Rosen in 1935: that thought experiment is about a situation in which two particles are prepared at a source and sent in opposite directions, with the possibility of measuring at least two different parameters on each particle; these parameters are fixed only shortly before the measurement, that is, when the particles are already separated by a distance in space that can be arbitrarily large. Bell's theorem establishes that it is not possible to account for the correlated measurement outcomes on the basis of the particles travelling on classical trajectories. More generally speaking, Bell proves the following: the probabilities for Alice's measurement outcome in her wing of such an experiment are not determined by the parameter she chooses to measure and the past state of the quantum system (which may include whatever there is in the past light-cone of her measurement operation). Quite to the contrary, the probabilities for Alice's measurement outcome are influenced by Bob's choice of the parameter to measure in his wing of the experiment and the outcome that he obtains, although Bob's choice of the parameter to measure and his outcome are separated by a spacelike interval from Alice's choice of the parameter to measure and her outcome; thus, no signal travelling at most with the speed of light could connect them.[3]

[3] See Bell's papers in Bell (2004, in particular the last one ch. 24), Goldstein et al. (2011) for an easily accessible presentation of Bell's theorem and Maudlin (2011) as well as Seevinck and Uffink (2011) for a detailed examination.

Consequently, the quantum formalism presents us with the following dilemma: on the one hand, a merely epistemological ready of the wave-function is ruled out in the general case; on the other hand, an ontological reading of the wave-function as providing us with a complete representation of physical reality commits us to acknowledging what Einstein termed “spooky action at a distance”.[4] Hence, it is not possible to read an ontology of the natural world off from the formalism of textbook quantum mechanics. In other words, applying a positivist or naturalized metaphysics to that formalism is a dead end. However, *a priori* reasoning can obviously not yield an ontology of quantum physics either. What we need in this case, as in the case of classical mechanics as set out by Newton, is a natural philosophy that accomplishes the following task: it provides for a formalism that grounds the algorithm of calculating probabilities for measurement outcomes of textbook quantum mechanics and that answers the physical questions left open by that algorithm (the question of what happens in the case of Einstein’s boxes is a physical one, not a philosophical one) together with setting out an ontology of the natural world, both coming in one package and thus being inseparable. In order to achieve that aim, we can use the three questions formulated in the preceding section as a guideline. As we employed Newton in order to reply to these questions in the context of classical mechanics, so we can turn to Bell in order to answer these questions in the context of quantum mechanics.

Consider the first question: *What are the physical objects?* One can summarize Bell’s reasoning about this question by means of the following four steps:

(1) Any observable phenomenon, including any measurement outcome, consists in the fact of something having a precise localization in physical space, such as, for instance, a pointer pointing upwards instead of downwards (see e.g. Bell 2004, p. 166). In other words, any measurement outcome consists in a certain distribution of matter in space.

(2) Macrophysical objects, including the devices that are used as measurement apparatuses, can be localized in physical space if and only if the microphysical objects that compose them are also localized.

(3) If one adopts common sense realism as well as experimental realism, macrophysical objects are localized even if no one observers them. Hence (from (2)), the microphysical objects that compose macrophysical objects are localized independently of whether or not anyone makes a measurement.

(4) Microphysical objects are localized when they build up macrophysical objects if and only if they are *always* localized. Otherwise, one would be committed to spooky action at a distance – a measurement operation at a certain location could then have the effect that a microphysical object instantaneously adopts a precise localization arbitrarily far apart in space.

This reasoning shows that there is no need to change the answer to the question *What are the physical objects?* when passing from classical to quantum mechanics. The basic ontology

4 That commitment could be avoided by refusing to acknowledge that there are any measurement outcomes at all, since it arises from the assumption of the collapse of the wave-function in order to take into account the fact that there are measurement outcomes (and, in general, well localized classical, macrophysical objects). Avoiding that commitment by denying that there are measurement outcomes is the line taken by the ontology of quantum physics going back to Everett (1957). See the papers in Saunders et al. (2010) for the contemporary discussion.

consists in matter distributed in a background space, more precisely in particles existing at points in space.

What has to be changed when passing from classical to quantum mechanics is the law for the temporal development of the distribution of matter in space, since classical trajectories of particles cannot yield the quantum mechanical probabilities for measurement outcomes. In other words, the answer to the question *What are the properties of the physical objects so that certain laws describe their behaviour?* has to change: the particles have to be taken to be endowed with other properties than in classical mechanics.

It is possible to simply add a specific quantum force to the classical forces in order to obtain particle trajectories that yield the quantum mechanical probabilities for measurement outcomes. This is done in that version of the quantum theory that goes back to Bohm (1952) in which a specific quantum force is admitted, known as quantum potential or pilot wave.[5] However, one can with good reason object that simply adding a quantum force when passing from classical to quantum mechanics is an *ad hoc* move: that force cannot be traced back to properties of the particles, as the gravitational force can be traced back to mass and the electromagnetic force to charge. Moreover, that force cannot be treated in terms of a field defined on physical space, for it does not permit to assign values to points of space-time. If the wave-function, which is supposed to stand for the quantum force on this view, represents a field, it can only be a field on configuration space, that is, the very high dimensional mathematical space each point of which corresponds to a possible configuration of the particles in physical space. However, it is entirely mysterious how a field on configuration space could influence the motion of particles in physical space.

Let us therefore go one step back and recall the motivation for taking the primitive stuff in space to be endowed with properties at all. We need the commitment to properties if we want something that determines the temporal development of the distribution of the primitive stuff in space. But it is a particular choice made by Newton and further pursued throughout classical physics to take the properties that do so to be such that they give rise to forces – such as mass providing for the force of gravitation, or charge yielding the electromagnetic force. In other words, it is a particular choice made by Newton and further pursued throughout classical physics to go for a law of motion that is second order, that is, being about acceleration, namely the temporal development of the velocity of the particles. A simpler choice would be to examine the temporal development of the position of the particles *tout court*, that is, to put forward a law of motion that is first order, being concerned with what determines the velocity of the particles, given their position. In other words, properties in this case are needed as that which fixes the velocity of the particles given only their position (and not an initial velocity in addition to an initial position).

There indeed is a quantum theory available that implements this choice, namely the dominant contemporary version of the theory going back to Bohm (1952) and cast in an elegant manner by Bell (2004, chs. 4 and 17), known today as Bohmian mechanics.[6] The Bohmian law for the temporal development of the distribution of matter in space is this one:

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5 See notably Holland (1993) for a detailed account and Belousek (2003) for a defence.

6 See Goldstein (2006) for a brief presentation and the papers in Dürr, Goldstein and Zanghì (2013) for a detailed exposition.

$$\frac{dQ}{dt} = v^{\Psi_t}(Q) \tag{1}$$

In this law, the quantum mechanical wave-function Ψ has the job to determine the velocity of the particles at a time *t*, given their position at *t*. The wave-function can perform this job because it can with good reason be regarded as referring to a property, namely a dispositional property of the particles that determines their temporal development by fixing their velocity.[7]

However, the wave-function that figures in equation (1) is the universal wave-function; consequently, *Q* stands for the configuration of *all* the particles in the universe. That is to say, the property that fixes the velocity of any particle at a time *t* given its position at *t* is not an intrinsic property of that particle. Quite to the contrary, there is only one instantiation of a holistic property of all the particles at *t*, represented by the universal wave-function at *t*, that determines the velocity of each particle at *t*. That is how Bohmian mechanics accounts for the non-local correlations brought out by the Einstein-Podolsky-Rosen thought experiment and Bell's theorem. In other words, the trajectories of the particles are not fixed by forces acting locally on them, but by a holistic property of all the particles taken together.

Let us now turn to the third question asked in the preceding section, namely *How do the physical objects and their properties explain the observable phenomena?* Suppose that it has to be acknowledged that we are ignorant of the exact initial particle configuration. Suppose furthermore that the initial particle configuration is typical in a precise mathematical sense. One can then derive the quantum mechanical algorithm for calculating probabilities for measurement outcomes in Bohmian mechanics.[8] Consequently, Bohmian mechanics grounds textbook quantum mechanics in the sense that it provides an ontology of the distribution of matter in physical space and a law for the temporal development of that distribution from which the textbook algorithm of calculating probabilities for measurement outcomes can be deduced.

Although, strictly speaking, the velocity of any particle at *t* depends on the position of all the other particles at *t* via the mentioned holistic property, Bohmian mechanics allows for the introduction of what is known as effective wave-functions, that is, wave-functions that apply to particular local configurations of particles while abstracting from the rest of the universe. Bohmian mechanics thereby is in the position to account for both the non-local correlations as brought out by Bell's theorem and for the classical, local character of the environment with which we are familiar.[9] Thus, in the case of the above mentioned thought experiment with one particle in a box, in this case, according to Bohmian mechanics, the particle moves on a classical trajectory in one of the two boxes, with operations performed on the other box having no influence on its trajectory. Hence, in brief, as regards the third question, there is no reason to change the answer to that question either when passing from classical to quantum mechanics: (a) all macrophysical objects are composed of microphysical particles and (b) all differences in macrophysical objects can be traced back to the position (arrangement) and the change of position (motion) of the microphysical particles. The only difference is that instead of intrinsic and thus local properties accounting for the motion of the particles, a holistic property of all the particles taken together does so.

7 See Belot (2012, pp. 77-80) for a sketch and Esfeld et al. (2013) for a detailed argumentation.

8 See Dürr, Goldstein and Zanghì (2013, ch. 2).

9 See Dürr, Goldstein and Zanghì (2013, ch. 5).

However, as mentioned at the end of the previous section, one can already conceive an ontology of Newtonian mechanics in terms of one instantiation of a holistic property of mass distribution at any time *t* that relates all the objects in the universe and that fixes how each of them changes its state of motion at *t*. By the same token, one can take the universal wave-function in quantum mechanics to refer to one instantiation of a holistic property that relates all the objects in the universe and that fixes the velocity of each of them, given the position of all the particles. But this latter holism is in any case more radical than the one that one can contemplate with respect to Newtonian mechanics: the universal wave-function in quantum mechanics does not represent the distribution of a property of objects (as there is in any case a mass distribution in Newtonian mechanics such that each object has a certain value of mass), but exactly one instantiation of a holistic property of all the particles taken together. That property determines the velocity of each particle, but it is not a property possessed by each particle – due to the non-separability of the wave-function, there is only one wave-function for the whole particle configuration. Nonetheless, quantum mechanics, like Newtonian mechanics, admits a possible world with only one particle as limiting case: that particle has a wave-function, and that wave-function represents the property of that particle which fixes its temporal development. To put it differently, for any possible world, there is exactly one universal wave-function representing the property that fixes the temporal development of the objects in that world, whatever their number may be.

Bohm's quantum theory, as set out by Bell, is generally perceived as implementing the most minimal change in ontology that one has to concede when passing from classical to quantum mechanics. One may go further and notably abandon the commitment to particles. Thus, other proposals to conceive matter in quantum mechanics notably include a continuous distribution of stuff in physical space (a mass density field)[10] and sparsely distributed discrete point events, known as flashes, which do not make up continuous trajectories or worldlines.[11] However, in any case, whatever the distribution of matter in physical space may be, there is no possibility to account for its temporal development on the basis of local and hence intrinsic properties, given Bell's theorem. On any account, the temporal development of the distribution of matter in physical space is fixed by a holistic and dispositional property instantiated by the matter distribution as a whole and represented by the universal wave-function.

That is the reason why quantum physics lends support to the view known as ontic structural realism: the mentioned holistic property is a structure, because it relates everything that makes up the distribution of matter in space. However, that property or structure is instantiated by something, namely the distribution of matter in space, in whatever entities that distribution may consist. Consequently, the distribution of matter in physical space, whatever types of entities constitute it, is at any time *t* individuated independently of that property or structure, on whatever individuation conditions may apply to particles, a mass density field, or flashes (for instance, particles and flashes are individuated by their position in space – there is a number *n* of particles or flashes in space at *t* given by the number of points that are occupied at *t*). Nonetheless, that holistic property or structure may provide for an intertemporal identity of the entities that constitute the distribution of matter in space – as in the case of Bohmian

10 See Ghirardi et al. (1995) and Monton (2004).

11 See Bell (2004, ch. 22) and Tumulka (2006).

particles, it fixes a continuous trajectory for each particle that is characteristic of the particle in question.

In short, there is a configuration of matter in space, and the reason why this configuration instantiates a certain structure or holistic property is that this structure or holistic property does the job of determining the temporal development of the distribution of matter in space and thereby also is able to account for measurement outcomes.[12] If, by contrast, one maintains that there are structures all the way down (as do French and Ladyman)[13] – so that there are no objects that instantiate the structures and that consequently are individuated independently of the structures in question –, one cannot let the structures perform the job of determining the temporal development of something and one thereby jettisons the possibility to account for measurement outcomes in quantum physics.

Elaborating on the mentioned holism in terms of ontic structural realism can also help to bring out the contrast with action at a distance. Bell's theorem rules out Einstein's epistemological view of the quantum mechanical wave-function, but we are thereby not committed to falling back to what Einstein considers as spooky action at a distance. Bohmian mechanics, conceived as a first order theory without a specific quantum force as sketched out above, can illustrate this issue: there is no question of a direct interaction among the particles in Bohmian mechanics – such an interaction would indeed be action at a distance. Instead of interacting directly with each other, the particles are related through the holistic property or structure that determines the velocity of each of them at a time t given the position of all of them at t. There is of course indirect interaction among the particles in that a local change in the arrangement of particles (e.g. fixing a parameter in a Bell-type experiment, opening or closing one slit in a double slit experiment, etc.) can influence the velocity of strictly speaking all the other particles, whatever their distance in space is – but it does so through the mentioned structure or holistic property instantiated by all the particles, by contrast to direct interaction among the particles.

When passing from quantum mechanics to quantum field theory and quantum gravity, the mentioned holism is not only confirmed, but moreover strengthened. In what is known as relativistic quantum field theory, despite its being relativistic, Bell's theorem applies: the probabilities for a certain event to occur at a given space-time point are not fixed by what there is in the past light cone of the event in question, but also depend on what happens at spacelike separated points (see Bell 2004, ch. 24). The main change with respect to quantum mechanics is the following one: whereas the quantum mechanical algorithm for calculating probabilities for measurement outcomes can be derived from an ontology that is committed to a fixed number of particles whose trajectories are determined by a holistic property instantiated by the configuration of all the particles, it seems that one has to make room for events of particle creation and annihilation in quantum field theory. Thus, if one retains the commitment to particles and if one takes particles to be substances, one has to allow for substances to come into and go out of existence. In any case, whatever one takes the distribution of matter in space to be, that distribution instantiates as a whole a structure or holistic property that fixes its temporal development and that is represented by the universal wave-function. In other words, there is in any case a good reason in quantum field theory to

12 See Esfeld and Lam (2011) as well as Esfeld (2013) for setting out ontic structural realism in that sense.

13 See notably French (forthcoming) and Ladyman and Ross (2007).

endorse the commitment to a holistic property of the distribution of matter in space that fixes its temporal development, even if that property no longer provides for an intertemporal identity of particles (as it does in Newtonian mechanics as well as in non-relativistic Bohmian mechanics).[14]

In quantum gravity, there no longer is a background space and a background time in which matter is inserted, but space and time are themselves treated as quantum objects. Accordingly, there no longer is a universal wave-function that develops itself in a background time. Quite to the contrary, the universal wave-function is stationary, the Schrödinger equation being replaced with the Wheeler-deWitt equation. Nonetheless, the universal wave-function can still be regarded as referring to a configuration of elementary objects, such as a configuration of elementary parts of space (or a configuration of elementary parts of space-cum-matter), and representing a holistic property of such a configuration that fixes the transition from one such configuration to the next one such that something approximating the classical space-time of general relativity theory is built up. In such a scenario, the holism that is characteristic of quantum physics is strengthened, since whatever relationship holds between the subsequent configurations of elementary objects is given entirely by the mentioned holistic property that is instantiated by any such configuration and that is represented by the universal, stationary wave-function.[15]

In sum, the crucial difference between classical and quantum mechanics is this one: in classical mechanics, there are dispositional properties of the particles that fix their temporal development in the sense of fixing the temporal development of their velocity (acceleration), and these properties can be conceived as intrinsic properties of each particle. As far as what is specific for quantum physics is concerned, there are no intrinsic properties of particles, but only one structure or holistic property that determines the temporal development of the distribution of matter in space (determining in the case of particles the temporal development of their position by fixing the velocity of each particle). Since Bell's theorem can with good reason be taken to put a constraint on any future physical theory, there is no prospect of going back to intrinsic properties in the ontology of the natural world. Relations will in any case have to be recognized as fundamental, as stressed by ontic structural realism. However, these relations are instantiated by objects, and one may conceive these objects as substances, even if one has to abandon some features that are traditionally associated with the notion of a substance.

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14 For attempts to formulate a Bohmian quantum field theory, see Bell (2004, ch. 19) and Dürr, Goldstein and Zanghì (2013, ch. 10) as well as Struyve (2011) for an overview of the state of the art.

15 See Dürr, Goldstein and Zanghì (2013, ch. 11) as well as Vassallo and Esfeld (2013) for a sketch of a Bohmian ontology of quantum gravity.

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